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CLINICAL REVIEW

The effects of sleep on prospective memory: A systematic review and meta-analysis

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SUMMARY

Prospective memory (PM) enables us to execute previously conceived intentions at a later time and is used when remembering to call a friend or submitting a proposal on time. Evidence that sleep benefits PM is presently mixed. Further, when a benefit is observed, it is unclear if this is achieved through improvements in strategic monitoring (maintaining an intention in mind and searching for cues) or spontaneous retrieval (an automatic process occurring without preparatory attention). We conducted a meta-analysis of 24 independent samples ($N = 165{,}432$) to quantify the effect of sleep on PM and gain clarity regarding the retrieval process benefitted by sleep. Cohen's d with 95% confidence intervals (CI_{95}) were derived using random-effects models. The benefit of sleep on PM was statistically significant and in the small to medium range ($d = 0.41$, $CI_{95} = 0.25–0.56$). Moreover, sleep did not appear to influence monitoring ($d = -0.11$, $CI_{95} = -0.40–0.17$). In contrast, the benefits of sleep are significantly greater when the likelihood of spontaneous retrieval is high ($d = 0.94$, $CI_{95} = 0.44–1.44$) versus low ($d = 0.45$, $CI_{95} = -0.02–0.93$), suggesting that sleep may leverage on spontaneous retrieval processes to improve PM. These findings inform theoretical models of sleep and PM that could sharpen strategies to improve memory function in vulnerable populations.

Introduction

Prospective memory (PM) refers to the ability to self-initiate previously conceived intentions and this enables us to execute future goals [1]. These intentions can be executed at a specific time (e.g., attending a meeting at 9 am) – time-based PM – or in response to the occurrence of an event (e.g., relaying an important message to a colleague the moment he arrives at the meeting) – event-based PM. PM tasks are ubiquitous in everyday situations, failures of which comprise 50–80% of all memory oversights experienced everyday [2–4]. As PM failures can have catastrophic consequences, e.g., forgetting an insulin injection, it is important to study antecedents of PM.

Recently, a number of studies have shed light on the importance of sleep in PM: sleeping after encoding an intention improved PM [5–8], whereas short sleep [9–14] and sleep deprivation [15–17] were associated with impaired PM. However, other studies reported no benefits of sleep over wake on PM [18–20] and no significant differences in PM between individuals with disturbed sleep and healthy controls [21,22]. Hence, the first aim of this study was to conduct a meta-analysis on previous work to collectively assess the effect of sleep on PM.

Another outstanding question regarding sleep and PM is the extent to which the latter is facilitated through strategic monitoring and/or spontaneous retrieval processes. In the present work, we adopt the Multiprocess framework [23,24] to examine retrieval processes. According to this framework, monitoring involves the allocation of attentional resources to keep the intention active in mind (e.g., holding in mind the intention to pass the message to your colleague) as well as to look out for the PM cue (e.g., attending to the door in anticipation of your colleague's arrival). In contrast, spontaneous retrieval is a reflexive associative process whereby intentions simply 'pop into mind'. For example, registering that a colleague has come through the door triggers automatic retrieval of

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Abbreviations: CI, confidence interval; PRISMA, preferred reporting items for systematic reviews and meta-analysis; PFC, prefrontal cortex; PM, prospective memory; REM, rapid eye movement; SD, sleep deprivation; SWS, slow wave sleep; TST, total sleep time.

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the intention to pass on a message [23,24]. Both retrieval processes may be engaged within the same task [25], and task conditions can influence the likelihood of spontaneous retrieval or monitoring processes.

Notably, a role for sleep in facilitating spontaneous retrieval has been proposed [5,7,8]. This is of particular relevance to persons who have limited attentional resources for holding an intention in mind while monitoring for the PM cue, for example, someone who is busily engaged in multiple tasks throughout the day, or an older adult with diminished attentional capacity. However, few studies have explored this by successfully contrasting sleep's effects on the two retrieval processes, a limitation which is compounded by the complexity of isolating spontaneous retrieval from monitoring [26]. It is difficult to definitively conclude which retrieval process is responsible for successful prospective remembering without corresponding physiological indices to confirm the underlying neurological process – unfortunately, all present studies on sleep and PM lack this feature.

Nonetheless, here, as a first attempt to examine which PM retrieval process sleep would preferentially benefit, we utilized available data from the literature and adopted the following reasoning: if an observed sleep improvement was *not* accompanied by increased monitoring, it may have been facilitated by spontaneous retrieval. However, as spontaneous retrieval cannot be measured directly, we asked instead whether sleep's benefit was *greater* when the likelihood of spontaneous retrieval was *higher*, which would suggest that sleep may be tapping on spontaneous retrieval processes to produce an enhancement of PM. Hence, we first sought out studies that showed a sleep benefit. A summary effect size was then computed for sleep's effect on monitoring. Next, for studies in which significantly better PM performance in the sleep group was *not* accompanied by significantly increased ongoing costs compared to the wake group, we examined whether the effect size of sleep on PM would be greater when the likelihood of spontaneous retrieval was high versus low. This approach enabled us to estimate the extent to which sleep's effects are boosted when spontaneous retrieval processes are more easily accessed.

Lastly, we explored whether the effect of sleep on PM varied depending on study factors, such as, sample age and PM type. Improvement of memory may vary with age [27,28] and we extended this evaluation to PM. PM tasks may be time-based or event-based [29]; however, whether sleep has similar effects on both kinds of PM remains unknown. We also examined if the heterogeneity in findings might be attributed to study type (experimental or observational), or whether PM and sleep were measured objectively or subjectively.

Methods

Literature search

Meta-analyses were performed using the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines. Computer and manual searches were conducted to identify published and unpublished studies written in English that examined the association of sleep with prospective memory in healthy individuals and individuals with sleep disorders between Jan 2010 to December 2018. For published studies, we searched four electronic databases – PubMed, PsycInfo, Web of science and Google scholar – for relevant articles using combinations of sleep-related keywords (‘sleep’, ‘sleep duration’, ‘habitual sleep’, ‘sleep quality’) and the keyword ‘prospective memory’. In addition, a manual search was conducted on four sleep journals that were likely to publish relevant studies (“Sleep”, “Journal of Sleep Research”, “Sleep Medicine”, “Journal of Clinical Sleep Medicine”). We also examined reference lists within relevant published articles to locate other studies.

For unpublished works, we searched for theses and dissertations on the databases OATD.org (open access theses and dissertations) and ProQuest using the same keywords and combinations. We did not find any unpublished studies examining the association between sleep and prospective memory in healthy individuals and individuals with sleep disorders.

Inclusion and exclusion criteria

We included studies into our meta-analyses that fulfilled the following criteria: 1) original article; 2) sleep as a) an independent variable examined as a primary manipulation, b) a group contrast involving a sleep disorder group and a healthy comparison group, or c) a continuous measure assessed with either objective or self-reported measures; 3) objective or self-reported assessment of PM; 4) report of sufficient descriptive or inferential statistics that could be converted to Cohen's *d*. We contacted authors to request for the relevant statistical information if it was not reported in the published article. We excluded studies that examined sleep in individuals with clinical conditions (e.g., multiple sclerosis) or cognitive impairments (e.g., mild cognitive impairment) as these might have contributed to deficits in PM.

For studies including multiple measures of sleep or PM, our selection of findings for final inclusion into the meta-analysis was guided by the principle of having a sufficiently broad representation of the multifaceted concepts of ‘sleep’ and ‘PM’. This was to ensure that our meta-analysis would not be biased by a particular operationalization of either term.

Ohayon et al. [30] reported the effects of both short ($\leq$5 h) and long habitual sleep (>8.5 h) on PM in older adults using the same reference group (7–8.5 h). As meta-analyses require independence of effect sizes, we included the effect size for the effect of long sleep instead of short sleep for two reasons: 1) the sample size for that group was larger ($n = 138$ versus $n = 113$), and 2) in healthy older adults, habitual long sleep is less frequently examined in the literature compared to habitual short sleep. Fine et al. [31] examined the association between several sleep parameters and PM, such as total sleep time (TST), sleep efficiency, wake after sleep onset, awakening length, and number of awakenings. Of these, we included only the relationship involving TST. Cavuoto et al. [14] conducted analyses on both objective and subjective measures of sleep, in which case, we selected objective measures over subjective measures as the former is more rare and valuable in observational studies. For studies involving multiple clinical groups, we calculated Cohen's *d* for the group contrast between the relevant sleep group (e.g., idiopathic rapid eye movement sleep behavior disorder [13,22,32] and insomnia [11,21]) and comparison group (e.g., healthy control). Lastly, Marcone et al. [22] assessed PM in several ways, such as using the Prospective and Retrospective Memory Questionnaire (PRMQ), the envelope test, and an event-based PM task performed on a computer (i.e., press the spacebar whenever a specific word appears during a trivia task). We chose to include results from the envelope test [33] because of its ecological nature which is particularly valuable in studies of PM that involve older adults [34].

Retrieval processes in prospective memory

Our meta-analysis based its conceptualization of retrieval processes and the way in which they are expressed behaviourally on the Multiprocess framework [23]. To detect *monitoring*, we adopted a resource allocation account of PM retrieval [35]. According to this theory, the utilization of a monitoring strategy is evidenced by costs to the ongoing task performance, such as reduced speed [35]. If sleep were to support monitoring, the sleep group would allocate more resources to monitor for the appearance of the PM cue and to retrieve the PM content. This would result in slower reaction times during the ongoing task in the retrieval session.

The overall likelihood of *spontaneous retrieval* may be experimentally increased by manipulating cue focality or salience, as well as the associativity between the cue and the action to be performed [23,36]. Cue focality refers to the degree to which performing the ongoing task supports cue processing, for example, having to detect 'tornado' instead of 'tor' while the ongoing task involves semantic rather than phonetic processing. High focality facilitates quicker detection of the PM cue [37]. Likewise, related cue–action associations (e.g., phone-unplug earphones), compared with unrelated cue–action associations (e.g., mirror-close the book), enable more rapid and reflexive delivery of the action to awareness [38].

To examine the retrieval process through which sleep improves PM, we adopted the following procedure: *for the 8 studies that demonstrated a benefit of sleep on PM* [5–8,15–17], we first determined whether overall monitoring, as indicated by ongoing task costs, was facilitated by sleep. Ongoing task costs were reported in six of the eight studies [5,7,8,15–17], all of which compared ongoing task performance (and PM task performance) after sleep and after wake. Thus, we derived the Cohen's *d* for the group contrast (sleep versus wake) on the reaction time measure in the ongoing task in the retrieval session. For studies that varied attentional demands of the ongoing task [5,16], we based our effect size calculations on the ongoing task conditions that were less resource demanding, as monitoring was more likely to be deployed in these conditions [36]. For studies employing a time-based PM task, time monitoring behavior as indexed by clock checks was used as a measure of strategic monitoring [15,17].

Then, for studies in which we determined that better PM performance in the sleep group was *not* accompanied by increased monitoring i.e., no significant group differences in ongoing task costs, we examined whether sleep's effect was *greater* when spontaneous retrieval was made *more likely* by task conditions. We were able to investigate this in three studies, which experimentally manipulated the overall likelihood of spontaneous retrieval [5,7,16] by varying cue focality [16], or the associativity between the cue and intended action [5,7]. For these studies, we derived and compared the Cohen's *d* for the summary effect size of sleep on PM in high and low likelihood conditions to assess the extent to which sleep's effects are boosted when spontaneous retrieval processes are more easily accessed.

Data extraction

Two researchers located the studies and determined whether they should be included based on the inclusion and exclusion criteria. Data was extracted independently by these two researchers, and any differences were resolved by discussion with a third researcher. The following information was extracted: first author's surname, year of publication, sample size, age information, prospective memory type (event-based or time-based), study type (experimental or observational), type of prospective memory measure (objective or subjective), type of sleep measure (objective or subjective), the relevant descriptive or inferential statistics for the sleep effects on PM performance as well as retrieval strategy. For studies that did not report Cohen's *d*, descriptive or inferential statistics were converted into Cohen's *d* values and its associated 95% confidence interval (CI_{95}) using standard formulas. Data were coded such that a positive Cohen's *d* value indicates a beneficial effect of sleep. By convention, the cutoff values for small, medium, and large effect sizes were 0.20, 0.50, and 0.80 respectively [39].

Study quality assessment

The quality of studies included in the meta-analysis was assessed with the Downs & Black quality index score system [40]. As some of the items in the original scale were not applicable to the current meta-analysis, we adopted the modified scale [41] which has five subscales assessing reporting, external validity, bias, confounding, and power, and has a maximum score of 18. All the studies were of satisfactory quality (13–17; Table 1).

Statistical analyses

Random-effects meta-analyses were conducted with Comprehensive Meta-Analysis Version 3.0 (Biostat, Englewood, NJ). Three meta-analyses were performed. In the first analysis, we computed summary effect sizes for the effect of sleep on prospective memory, Publication bias was evaluated using Egger's test of intercept [42] and Duval and Tweedie's trim and fill method [43]. In the second and third analyses, in order to examine whether sleep preferentially supports monitoring or spontaneous retrieval processes, we quantified the effects of sleep on monitoring as well as the effects of sleep when the overall likelihood of spontaneous retrieval was high and low. While 95% confidence intervals (CI_{95}) are employed to estimate the statistical significance of a single effect size, in order to statistically test the *difference* between effect sizes in the high and low likelihood conditions, following previous approaches, 84% confidence intervals (CI_{84}) were derived [44,45]. In a random effects model, the absence of an overlap between 84% confidence intervals indicates that the two effect sizes are significantly different [46,47].

For each of these three meta-analyses, between-study heterogeneity was indicated by Cochran's Q and the I^2 statistic. While the Q statistic provides information on the significance of the heterogeneity of effect sizes, the I^2 index is a measure of the magnitude of the extent of true heterogeneity, versus sampling error, between studies. Percentages of 25%, 50%, and 75% indicate low, medium, and high heterogeneity, respectively [48].

To deal with heterogeneity in effect sizes across studies, we conducted sub-group analyses to examine possible moderators of effect size. For the overall effect of sleep on PM in which significant heterogeneity was found (see Results for more details), we identified five categories of study features that could potentially contribute to the heterogeneity in effect sizes: 1) age group examined (younger, 15–30 y; older, 40–93 y), 2) prospective memory type (event-based, time-based) 3) study type (experimental, observational), 4) prospective memory measure (objective, subjective), and 5) sleep measure (objective, subjective). Subgroup analyses were conducted to quantify the effect size of sleep on prospective memory for each of the sub-categories separately. As three studies [10,12,21] recruited from a wide age range, e.g., 16–80 y and young and older age groups could not be separated, these studies were excluded from the 'age' sub-group analysis. Prospective memory type could not be separated in two studies [12,30], which were excluded from the relevant sub-group analysis.

Results

Characteristics of included studies

Twenty studies met the selection criteria (Fig. 1). Of these, 10 were experimental studies and 10 were observational studies.

Table 1
Description of studies included in the meta-analysis.

First author	Publication year	n	Quality score	Mean age ± SD or range	PM type	Study type	Type of PM measure	Type of sleep measure	Sleep measure/contrast
Barner et al. [18]	2017	94	15	22.69 ± 2.98	Event-based	Experimental	Objective	Objective	Post-encoding sleep vs wake
Bezdicek et al. [32]	2017	90	15	59–76	Event-based Time-based	Observational	Objective	Objective	iRBD vs controls
Cavuoto et al. [14]	2016	173	17	65–89	Event-based	Observational	Objective	Objective	Actigraphy
Diekelmann et al. [5]	2013	35	15	20–28	Event-based	Experimental	Objective	Objective	Post-encoding sleep vs wake
Diekelmann et al. [6]	2013	56	15	23.90 ± 4.41	Event-based	Experimental	Objective	Objective	Post-encoding sleep vs wake; Post-encoding SWS-rich sleep vs REM-rich sleep
Esposito et al. [15]	2015	50	15	20–24	Time-based	Experimental	Objective	Objective	Pre-encoding sleep deprivation vs well rested
Fabbri et al. [10]	2014	254	13	16–80	Event-based	Observational	Objective	Objective	Good sleepers vs bad sleepers
Fabbri et al. [21]	2015	167	14	16–80	Event-based	Observational	Objective	Objective	Insomnia vs controls
Fine et al. [31]	2018	132	15	55–93	Event-based	Observational	Objective	Objective	Actigraphy
Grundgeiger et al. [16]	2013	58	14	20–21	Event-based	Experimental	Objective	Objective	Pre-encoding sleep deprivation vs well rested
Kyle et al. [11]	2017	163,077	17	40–69	Event-based	Observational	Objective	Subjective	Frequent insomnia symptoms vs controls
Leong et al. [20]	2018	59	15	15–18	Event-based	Experimental	Objective	Objective	Post-encoding partial sleep deprivation (5 h TIB) versus 9 h TIB
Leong et al. [19]	2019	59	14	14–19	Event-based	Experimental	Objective	Objective	Post-encoding sleep vs wake
Leong et al. [7]	2019	49	15	19–24	Event-based	Experimental	Objective	Objective	Post-encoding sleep vs wake
Li et al. [13]	2018	49	14	55–87	Event-based Time-based	Observational	Objective	Objective	iRBD vs controls
Marcone et al. [22]	2018	45	13	57–76	Event-based	Observational	Objective	Objective	iRBD vs controls
Mcbean et al. [12]	2016	172	15	20–61	Not separable	Observational	Subjective	Subjective	PSQI
Occhionero et al. [17]	2017	50	14	20–30	Time-based	Experimental	Objective	Objective	Pre-encoding sleep deprivation vs well rested
Ohayon et al. [30]	2002	715	17	≥60	Not separable	Observational	Subjective	Subjective	Long sleep (>8.5 h) vs controls (7–8.5 h)
Scullin & McDaniel [8]	2010	48	15	Undergraduates	Event-based	Experimental	Objective	Objective	Post-encoding sleep vs wake

iRBD, idiopathic rapid eye movement sleep behavior disorder; PSQI, Pittsburg sleep quality index; REM, rapid eye movement; SWS, slow wave sleep; TIB, time in bed.

Some studies reported on analyses from a few experiments [18,49], and separately for different sub-groups [12], resulting in a total of 24 independent samples. Overall, the meta-analysis included 165,432 individuals from 10 countries (Australia, Canada, China, Czech Republic, Germany, Italy, Singapore, Switzerland, United Kingdom, United States of America), ranging from 15 to 93 y. The 10 experimental studies included 558 individuals while the 10 observational studies included 164, 874 individuals with one study contributing 163, 077 individuals [11].

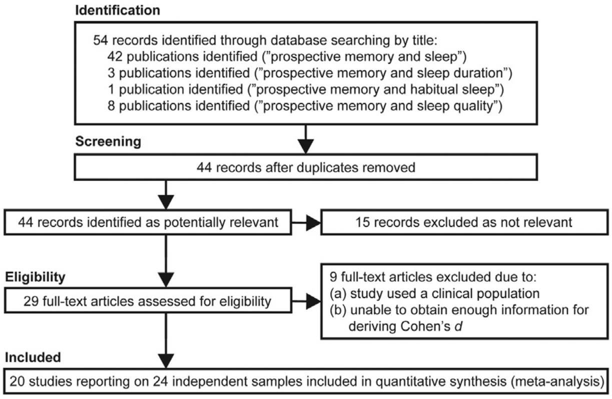

Fig. 1. Flow chart depicting the results of the systematic literature search following inclusion and exclusion criteria.

Overall sleep effect on PM

Cohen's *d* from 24 samples are illustrated in the forest plot (Fig. 2). Sleep significantly benefitted PM with a small to medium effect size (Cohen's $d = 0.41$, $\text{CI}_{95} = 0.25–0.56$, Table 2). As one sample [11] had a much larger sample size than the rest and could therefore dominate the results, we conducted a sensitivity analysis without including the data from this study. We found that results remained largely the same, and the overall effect of sleep remained significant (Cohen's $d = 0.45$, $\text{CI}_{95} = 0.28–0.61$, Table S1).

For the overall sleep effect on PM, publication bias was observed (Egger's test: $p < 0.001$) and is illustrated in a funnel plot whereby effect sizes of studies are plotted against their standard errors (Fig. 3). In the absence of publication bias, a funnel plot would be inverted and symmetrical. After adjusting for bias using Duval and Tweedie's trim and fill method [43] in which nine studies were imputed, the average effect size remained statistically significant ($d = 0.16$, $\text{CI}_{95} = 0.02–0.30$).

Effects of sleep on retrieval processes in PM

Cohen's *d* for the effect of sleep on strategic monitoring was based on six independent samples (Fig. 4). Sleep did not

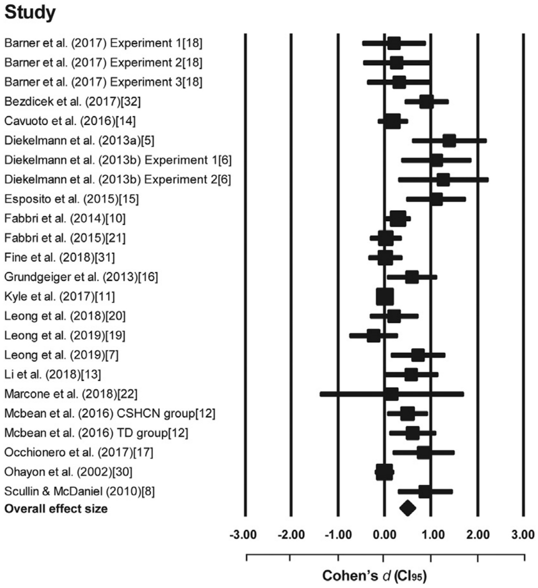

Fig. 2. Forest plot illustrating Cohen's *d* values and 95% confidence intervals (CI_{95}) derived from studies examining the effect of sleep on prospective memory. Positive values indicate a beneficial effect of sleep. CSHCNs, parents with children with special healthcare needs; TDs, parents of typically developing children.

Table 2
Cohen's *d* and 95% confidence intervals of the effects of sleep on prospective memory and retrieval processes.

	k	Cohen's *d*	CI_{95}	
			Lower	Upper
Overall effect of sleep on PM	24	0.41	0.25	0.56
Effect of sleep on monitoring	6	−0.11	−0.40	0.17
Effect of sleep on spontaneous retrieval				
High likelihood	3	0.94	0.44	1.44
Low likelihood	3	0.45	−0.02	0.93
By age group				
Younger	13	0.61	0.35	0.87
Older	7	0.18	−0.01	0.36
By PM type				
Event-based	19	0.39	0.21	0.57
Time-based	4	0.61	0.22	1.00
By study type				
Experimental	13	0.61	0.35	0.87
Observational	11	0.23	0.08	0.39
By PM measure				
Objective	21	0.44	0.26	0.62
Subjective	3	0.32	−0.10	0.75
By sleep measure				
Objective	20	0.47	0.29	0.66
Subjective	4	0.16	−0.05	0.36

k, number of independent samples; CI_{95}, 95% confidence intervals; PM, prospective memory.

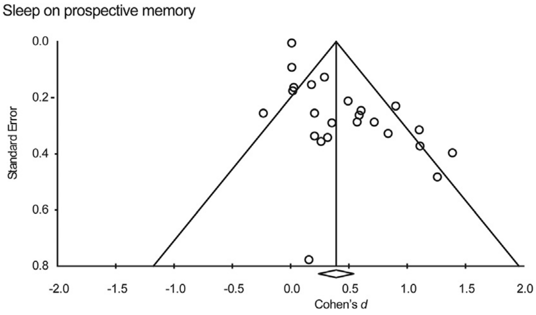

Fig. 3. Funnel plot for meta-analysis of the effect of sleep on prospective memory.

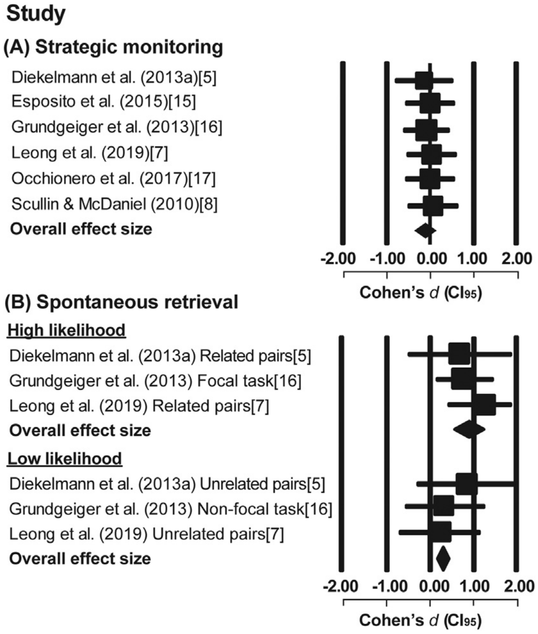

Fig. 4. Forest plot illustrating Cohen's d values and 95% confidence intervals (CI95) derived from studies examining the influence of sleep on retrieval processes in prospective memory – strategic monitoring and spontaneous retrieval. Positive values reflect (A) a greater degree of monitoring (i.e., greater ongoing task costs) in the sleep group compared to the wake group and (B) a beneficial effect of sleep in studies manipulating the likelihood of spontaneous retrieval wherein related cues and actions and focal tasks were more likely to engage spontaneous retrieval.

significantly increase strategic monitoring in PM ($d = -0.11$, $CI_{95} = -0.40 - 0.17$, Table 2). Heterogeneity in effect sizes across studies was not significant ($Q = 7.90$, $p = 0.16$, $I^2 = 36.69\%$).

In contrast to the effects on monitoring, we found that sleep's benefit was greater when the overall likelihood of spontaneous retrieval was increased by focal cues or high associativity between cues and intended actions ($d = 0.94$, $CI_{95} = 0.44–1.44$, Fig. 4) than when the likelihood of spontaneous retrieval was low ($d = 0.45$, $CI_{95} = -0.02 - 0.93$). This difference was statistically significant as there was no overlap between the 84% confidence intervals of the summary effect sizes ($CI_{84} = 0.58–1.24$ and $CI_{84} = 0.22–0.53$). This suggests that successful prospective remembering after a period of sleep may be due to the latter tapping on spontaneous retrieval processes rather than driven by monitoring. However, as Cohen's *d* for the effect of sleep on spontaneous retrieval was based on three independent samples, this finding should be treated with caution. Heterogeneity in effect sizes across studies was not significant in either the high ($Q = 0.25$, $p = 0.88$, $I^2 = 0.00\%$) or low likelihood conditions ($Q = 0.76$, $p = 0.68$, $I^2 = 0.00\%$).

Sub-group analyses

As there was significant heterogeneity in effect sizes across studies included in deriving the overall effect of sleep on PM ($Q = 101.51$, $p < 0.001$, $I^2 = 77.34\%$), five categories of study features that could potentially contribute to the variability in effect sizes of sleep on PM were examined: 1) age group, 2) prospective memory type, 3) study type, 4) prospective memory measure, and 5) sleep measure.

Sleep effect on PM by age group

Based on the age range of the sample in each study, we categorized studies into a ‘younger’ group (age range: 15–30 y, k = 13) and an ‘older’ group (age range: 40–93 y, k = 7). Sub-group analyses revealed a medium effect size in the younger age group ($d = 0.61$, $CI_{95} = 0.35–0.87$, Table 2), but a small and marginally non-significant effect in the older age group ($d = 0.18$, $CI_{95} = -0.01 - 0.36$).

Sleep effect on PM by PM type

Sub-group analyses revealed a medium effect size of sleep for time-based tasks ($d = 0.61$, $CI_{95} = 0.22–1.00$, k = 4) but a small effect size for event-based tasks ($d = 0.39$, $CI_{95} = 0.21–0.57$, k = 19). As the former was derived based on only four samples, this finding should be viewed as preliminary.

Sleep effect on PM by study type

Sub-group analyses were conducted to quantify the effect size of sleep on PM for experimental (k = 13) and observational studies (k = 11) separately. While experimental studies revealed a significant benefit of sleep on PM which was of a medium effect size ($d = 0.61$, $CI_{95} = 0.35–0.87$), the effect of sleep derived from observational studies was still statistically significant though in the small range ($d = 0.23$, $CI_{95} = 0.08–0.39$). Notably, all experimental studies comprised participants in the younger age group. Hence, these two sub-groups (experimental, younger) were made up of the same 13 samples, resulting in the same effect size values for both sub-groups.

Among the experimental studies, we also examined effects of sleep separately for memory consolidation and sleep deprivation studies. Both design types yielded similar medium effect sizes (sleep deprivation studies: k = 4, $d = 0.65$, $CI_{95} = 0.27–1.03$; memory consolidation studies: k = 9, $d = 0.59$, $CI_{95} = 0.23–0.95$).

Sleep effect on PM by PM measure

Sub-group analyses found that for studies employing objective measures of PM (e.g., task-based, k = 21), the effect of sleep was statistically significant with a medium effect size ($d = 0.44$, $CI_{95} = 0.26–0.62$). In comparison, the effect size yielded from the three studies employing subjective measures of prospective memory (e.g., PM complaints, k = 3) was only slightly smaller numerically, but nonetheless was not statistically significant ($d = 0.32$, $CI_{95} = -0.10 - 0.75$) likely due to the small k involved.

Sleep effect on PM by sleep measure

The effect derived from studies employing objective sleep measures (k = 20), e.g., actigraphy, was statistically significant and had a medium effect size ($d = 0.47$, $CI_{95} = 0.29–0.66$), while the effect from those studies employing subjective sleep measures (k = 4), e.g., self-reported sleep duration, was not significant ($d = 0.16$, $CI_{95} = -0.05 - 0.36$). Notably, 20 out of 21 studies that employed objective measures for prospective memory also employed objective measures of sleep, leading to similar estimates of effect sizes (Table 1).

Discussion

The present meta-analysis analyzed 20 studies that examined the impact of sleep on PM. Based on 24 independent samples, we found that sleep had a significant small to medium benefit on PM which varied depending on age and PM type such that studies performed in younger participants and employing time-based PM tasks appeared to yield larger effect sizes compared to those involving older participants and event-based PM tasks. Notably, after adjusting for publication bias, the average effect size of sleep on PM remained statistically significant.

Lastly, when the overall likelihood of spontaneous retrieval was high, sleep had a large and statistically significant benefit on prospective memory. In contrast, when the likelihood of spontaneous retrieval was low, this effect size was considerably reduced and was no longer significant. These findings suggest that sleep may benefit prospective memory by leveraging on spontaneous retrieval processes. In contrast, sleep-related improvements in PM were not accompanied by increases in overall monitoring. In the following sections, we first discuss the potential pathways through which sleep might support PM, followed by how age and PM type may moderate the effect of sleep on PM.

Passive and active roles of sleep

While PM may be considered a type of associative memory as it involves associations between cues and actions to be executed, PM is distinguished from retrospective memory due to its prospective component, which refers to the *self-initiated* retrieval of an action at a specific time or in response to a specific event in the future that must occur *without* an external reminder [50]. Nonetheless, successful PM requires both the prospective component (i.e., self-initiated timely retrieval) as well as the retrospective component (i.e., retrieval of the content of the intention). Similar to its roles in retrospective memory [51,52], sleep may play both a passive and an active role in the consolidation of PM.

Consolidation is a process whereby memories become stabilized and resilient to interference, and are therefore more likely to be successfully retrieved later on. Sleep may benefit memory for intentions in part by *passively* preventing interference from stimuli encountered during waking episodes, thereby attenuating forgetting [53]. This interference account is supported by the poorer PM performance observed after prolonged periods of wakefulness [9–13], sleep deprivation [15–17], and wake-filled retention intervals [5–8]. For example, Fabbri and colleagues found that poor sleepers, having shorter TST and longer awakenings compared to good sleepers, had diminished PM [10].

However, sleep may also play an *active* role in the consolidation of PM by initiating physiological processes within the neurochemical environment of sleep to strengthen memory traces. The most compelling line of evidence comes from studies that have identified specific features of sleep that facilitate PM consolidation through the spontaneous replay of memory traces alongside synaptic downscaling, with slow wave sleep (SWS) playing a significant role in this process [54–56]. In support of this, Diekelmann and colleagues found that in young adults, obtaining SWS-rich sleep after encoding intentions resulted in better prospective memory compared to post-encoding REM-rich sleep [6]. Their finding has been corroborated by our recent study performed in a similar age group, which found that greater amount of post-learning SWS was significantly associated with a higher percentage of successfully executed intentions [7]. A pertinent question is whether SWS's effects on PM are primarily driven by its improvement for the retrospective component of PM. Notably, our study which found better PM with greater amounts of post-learning SWS included 8 cue–actions pairs [7]. The high retrospective memory load may have led to greater SWS involvement in the processing of intentions for later retrieval. However, given that SWS was found to be important even when the PM task was far simpler e.g., informing the experimenter that a wrong stimulus was presented [6], it would appear that SWS also plays a role in the prospective component i.e., the timely execution of the intention. An interesting question for future experiments is whether the contributions of SWS or other sleep stages e.g., REM, to PM performance vary as a function of retrospective memory load.

Although there have been no studies reporting significant associations between other sleep stages and PM, this does not preclude the possibility of different stages of sleep working dynamically to support PM function. It is possible that REM sleep may also play a role in PM since REM sleep has been suggested to be important for memories that have future relevance [57]. Future studies should explore whether adjusting other parameters of the PM task might reveal a greater involvement of REM sleep. For example, emphasizing the behavioural importance of the task or making it more ecological might increase the reliance on REM sleep.

Sleep may also benefit PM through the overnight restoration of brain regions essential for PM. Neuropsychological and neuroimaging studies point to the importance of anterior prefrontal cortex (PFC) in supporting PM functions, through the maintenance of the intentions [58–60], and possibly encoding and retrieval phases as well [61,62]. It is possible that sleep might support PFC function by facilitating an overnight deactivation [63] which occurs alongside bursts of spontaneous activity [64]. This nightly interlude may restore the PFC for the PM functions it performs during wake. That the PFC might be particularly dependent on sleep is also seen from the deleterious effects that result when sleep's restorative functions are prevented, such as in sleep deprivation. For example, a night of total sleep deprivation significantly impaired performance on a time-based PM task such that only 32% of sleep-deprived participants remembered to execute an intention compared to 80% of those who slept [15].

Sleep's benefit on spontaneous retrieval: a neurological explanation

The present meta-analysis found that sleep's benefit on PM was more prominent when the likelihood of spontaneous retrieval was higher ($d = 0.94$, $\mathrm{CI}_{95} = 0.44–1.44$) compared to lower ($d = 0.45$, $\mathrm{CI}_{95} = -0.02–0.93$). In contrast, sleep-related improvements in PM were not accompanied by increased use of monitoring strategies in PM ($d = -0.11$). Notably, successful PM in the context of a non-significant increase in monitoring is suggestive that intentions were executed via spontaneous retrieval [36]. Together, these findings suggest that sleep may preferentially leverage on a spontaneous retrieval process whereby encountering the cue automatically activates the associated intended action. That sleep enables a target stimulus to bring to mind the requisite intention without drawing attention from an ongoing task is of great value to individuals who struggle with dividing attention. How does sleep accomplish this?

Drawing on findings from the associative memory literature, it is likely that sleep facilitates a spontaneous retrieval process through the overnight strengthening of cue–action associations [51,52], potentially via the SWS-mediated synchronized reactivation of hippocampal neural assemblies [49]. These strengthened associations may benefit from higher resting levels of neural activation [65], thereby requiring a lower threshold for cues to trigger their spontaneous retrieval the next day. Hence, sleep may play a dual role in strengthening the content of the intention as well as its spontaneous retrieval at the appropriate moment. Sleep loss may disrupt this process, as recent evidence has also shown that the stability of neural representations is reduced when one is sleep deprived [66], which may potentially affect the quality of stored intentions, the levels of resting activation, and the increase in activation required for successful retrieval.

Sleep's influence on monitoring processes

In the present meta-analysis, we found that sleep did not significantly impact monitoring. Surprisingly, even under conditions of experimental sleep deprivation (SD) which are known to have deleterious effects on sustained attention [67], poorer PM was not clearly linked to impaired monitoring as the SD and control groups did not differ in ongoing task costs [15–17,20]. SD does not appear to affect resources required for monitoring in PM, as Grundgeiger and colleagues found that compared to well-rested individuals, sleep deprived participants did not do worse even in the more resource demanding condition. This pattern is unexpected, considering that monitoring is assumed to draw on limited attentional resources which may be further depleted by SD [68]. These findings appear to contrast a large body of work showing that sleep deprivation results in significantly reduced activation in the frontoparietal network [69–71], an area which supports monitoring in PM [72,73].

Nevertheless, it is possible that SD did not reduce resources for monitoring per se, but rather, impaired PM by reducing overall arousal [16]. It is possible that a global reduction in arousal due to SD could have disrupted other components of monitoring, such as rehearsal processes which keep the intention active in mind. Indeed, SD has been shown to impair articulatory rehearsal [74,75]. An important goal for future studies is to investigate how SD impacts different components of monitoring processes using tasks in which they can be dissociated.

An alternative explanation for the null effect of sleep on monitoring may be that individuals performing a PM task are not continuously, but rather transiently monitoring for the PM cues. As such, the SD-induced slowing in reaction times during the ongoing task may be compensated for when sleep-deprived individuals rest from monitoring and devote all attentional resources to the ongoing task, thereby responding faster in those trials. Importantly, averaging ongoing task costs across all trials cannot distinguish between transient and continuous monitoring. Scullin and colleagues have proposed that individuals engage in monitoring and spontaneous retrieval dynamically, fluctuating between the two retrieval processes even in task conditions whereby one or the other is made more likely through experimental manipulation of focality or cue associativity [25]. Presently, there is a lack of sleep studies examining dynamic monitoring, and future studies should employ more sophisticated reaction time statistical techniques to inform newer theories on mechanisms of sleep on monitoring.

A final possibility to consider is that sleep may benefit PM by rendering monitoring strategies *more* efficient, such that fewer resources are necessary to monitor for cues. This would be supported when relative to a no-PM control group, sleep and wake groups show significant, but similar, ongoing task costs despite better PM performance in the sleep group. This highlights the importance for future studies to include a no-PM control group which will enable these accounts to be distinguished.

Lastly, in time-based PM, monitoring is commonly expressed as the frequency of clock checking. In line with findings from event-based PM tasks, Esposito and colleagues did not find clock-checking behavior on a time-based PM task to be impaired by SD. However, the sleep-deprived participants showed poorer time-based PM performance, suggesting that in a SD state, participants retained the ability to monitor the clock time, but did not apply this knowledge to the PM task at hand [15]. Interestingly, this dovetails with the finding that some aspects of monitoring, particularly of implicit temporal distributions, are not affected by SD [76]. This raises questions about whether sleep has dissociative effects on components of monitoring in PM, which may include but are not limited to search as well as rehearsal processes that keep the intention active. The paucity of experimental studies on sleep and PM retrieval processes limits our conceptual and mechanistic understanding of the sleep-PM relationship. Further, physiological data is needed to inform theories on how components of monitoring evolve across a task, and how sleep might impact neural pathways supporting monitoring in PM.

Moderating influences of age and PM type

In this study, we found that age moderated the effect of sleep on PM such that benefits were medium in young adults ($d = 0.61$), while in older adults, a small, though marginally non-significant, effect was still found ($d = 0.18$). Notably, the declining benefit of sleep on PM with age may be linked to age-related alterations in sleep features. In older adults, SWS, found to be important for PM, is estimated to decrease by approximately 2% per decade of age [77], and the slow oscillations that characterize SWS occur less frequently and with reduced amplitudes [78]. Indeed, age-related reductions in overnight memory retention [79,80] have been linked to decreased SWS [81,82]. In addition, age-related changes in brain parenchyma, such as PFC regions, have been associated with disrupted SWS generation and propagation [83]. Given that reductions in PFC volume are also likely to impact PM directly, it is plausible that older adults with more atrophy in PFC regions may receive less benefits from sleep. However, to address this, more neuroimaging studies will be needed.

PM type also moderated the effects of sleep on PM, whereby the benefit of sleep was numerically greater for time-based tasks ($d = 0.61$) compared to event-based tasks ($d = 0.39$). While event-based PM tasks are performed in response to cues that are monitored for or responded to as a result of spontaneous retrieval, time-based tasks are wholly self-initiated without cues, and performance may be dependent on effective strategy, for example, first calibrating one's subjective passage of time with the external clock, then adopting a pattern of increased clock checking closer to the stipulated time [84]. Other neurological functions are also important for successful time-based PM, such as accurate time estimation [85,86], time monitoring [87,88], as well as the ability to integrate temporal information with the prospective memory action [17,89]. Poor sleep may not only have deleterious effects on the employment of effective strategies, but may additionally undermine time-based PM tasks by impairing the various functional components involved [15].

Limitations and future studies

Our meta-analysis can only provide preliminary evidence for sleep's ability to leverage on spontaneous retrieval and thus, benefit PM. This is because the majority of published sleep studies that have sought to address the retrieval processes underlying PM have predominantly examined strategic monitoring, inferring sleep's benefit on spontaneous retrieval based on the *absence* of any sleep effect on monitoring. Only a small number of studies ($k = 3$) have involved an experimental manipulation of the likelihood of spontaneous retrieval. While in future studies, the overall likelihood of spontaneous retrieval should be manipulated through varying focality, cue salience, or the associativity between cues and actions, greater care must also be taken to discourage sustained monitoring. For example, this can be done by including a low number of PM cues, de-emphasizing the PM task while reminding participants of the importance of the ongoing task, delaying the onset of the first PM target, or even telling participants that the PM target will only be presented to a small percentage of all participants [26].

Even so, these manipulations are unable to definitively dissociate between retrieval processes. It is imperative that behavioural measures are combined with physiological tools such as eye-tracking or fMRI to confirm that participants are relying on spontaneous retrieval to execute the intention. For example, spontaneous retrieval may be supported by eye tracking data showing a PM cue processing-dependent change in fixation on an area designated for the PM task. Alternatively, using fMRI data, spontaneous retrieval may be indicated when the PM task is successfully executed despite lack of monitoring-related activation prior to the appearance of a PM cue i.e., absence of sustained aPFC or dorsal frontoparietal network activation. Importantly, physiological measures need to be analyzed with reference to a control condition within which performance and physiological indicators on the ongoing task without the PM task can be assessed [26].

Secondly, our findings on sleep's effects on monitoring are based on costs to ongoing task performance which is indicated by increased reaction time. However, these measures cannot inform on the specific monitoring strategy used. Specifically, they cannot distinguish between continuous monitoring, transient monitoring and dynamic monitoring wherein spontaneous retrieval is periodically employed. Future studies should adopt more sophisticated statistical approaches, such as ex-Gaussian or other reaction time distribution models, to delineate how monitoring is expressed and evolves over the course of a PM task.

Thirdly, in the present meta-analysis, age is confounded with study type as the ‘younger’ and ‘experimental studies’ sub-groups were made up of the same 13 independent samples. Hence, it is uncertain whether the larger effect sizes are associated with younger ages or the experimental nature of the studies. As mentioned previously, while SWS is important for PM in young adults [5,7], it remains uncertain whether this relationship is consistent in older adults [27]. Hence, studies using polysomnography on diverse age groups will be particularly important to investigate these potential age-related changes.

Fourthly, only one study has examined the association between long sleep (>8.5 h) and PM. While the relationship between short sleep duration and poor health outcomes has been well-documented [90], recent evidence suggests that long sleep is also associated with adverse cognitive [91] and health [92] outcomes. In view of this, more studies are needed to clarify the long sleep effect on PM function.

In addition, more studies examining the specific sleep features associated with sleep-based PM effects are needed. This would be aided by the experimental manipulation of SWS, or other sleep features, through acoustic stimulation or other techniques to augment or eliminate particular features of sleep. Importantly, if it is found that age-related reductions in SWS can account for poorer PM documented in older adults [37], future studies should focus on interventions that can boost SWS and memory function in at-risk older individuals.

Lastly, another possible area for future research concerns boundary conditions for sleep's benefit on spontaneous retrieval processes in PM, for example, investigating whether atrophy in the hippocampus, which is proposed to underlie associative retrieval, may moderate sleep-related improvements in PM. Importantly, findings would inform neuropathological models of sleep and PM that would be of clinical relevance especially for individuals with diminished hippocampal integrity, such as patients with sleep disorders [93,94] or older adults [95].

Conclusions

This meta-analytic review found that sleep has a significant small to medium benefit on PM, and appears to enhance PM performance by facilitating spontaneous retrieval processes. These findings inform theoretical models of sleep and PM that could inform strategies to improve PM function in individuals with limited attentional capacities, such as older persons.

Practice points

1. Sleep has a significant small to medium benefit on prospective memory.
2. Sleep appears to enhance prospective memory by leveraging on spontaneous retrieval processes.

Research agenda

1. While slow wave sleep plays a key role in prospective memory in young adults, this relationship may change with age. These age-related changes should be addressed in future studies involving diverse age groups.
2. Future sleep work should experimentally manipulate the extents of strategic monitoring and spontaneous retrieval with corresponding physiological indices so as to more definitively establish the prospective memory retrieval processes benefited by sleep.
3. Future studies should focus on interventions that can boost sleep and prospective memory function in at-risk persons, such as older individuals and patients with sleep disorders.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smrv.2019.05.006.

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